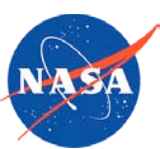




JANNAF Lessons Learned Panel Discussion

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AS-510 Stage Separation

◆ Lesson: There are NO Small Changes

◆ Background – Saturn V Integrated Vehicle Change Processed:

- Purpose: Increased payload to the Moon
- Change:
 - Eliminate the ullage settling motors on the S-II stage
 - Eliminate four of the eight retro motors on the S-IC Stage.
 - Delay stage separation and retro motor firing by an additional 1 second to increase separation distance.
- Effective: AS-510 was the first flight that incorporated the change.



AS-510 Stage Separation

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Results of the Change

Excerpts from the AS-510 Flight Evaluation Report

- ◆ S-IC/S-II first and second plane separations were accomplished with no significant attitude deviations.
- ◆ S-IC retro motors performed as expected.
- ◆ Separation distance was less than predicted.
- ◆ S-II exhaust plume at engine start resulted in a more severe environment at the S-IC forward LOX dome and resulted in S-IC telemetry system damage.
- ◆ Analysis indicates that with an S-IC stage having only four retro motors, failure of one retro motor to ignite would result in marginal separation distance and, in the 3 sigma case, re-contact of the two stages.

Implication: We could have lost the vehicle!

Post-Flight Assessment of Separation Distance

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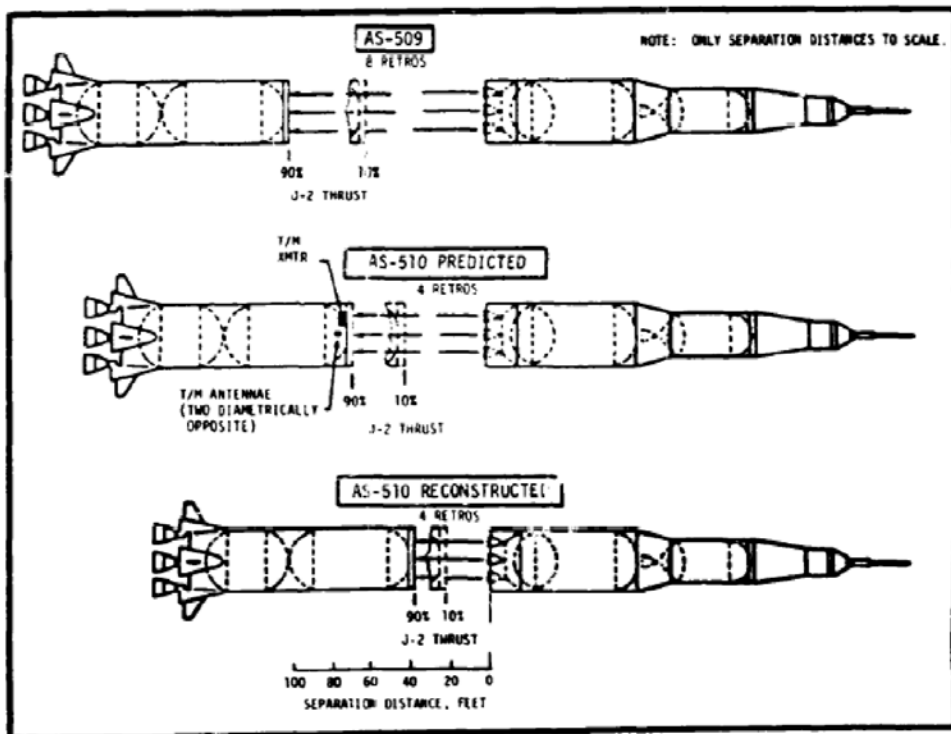


Figure 10-14. Saturn V Staging Motion

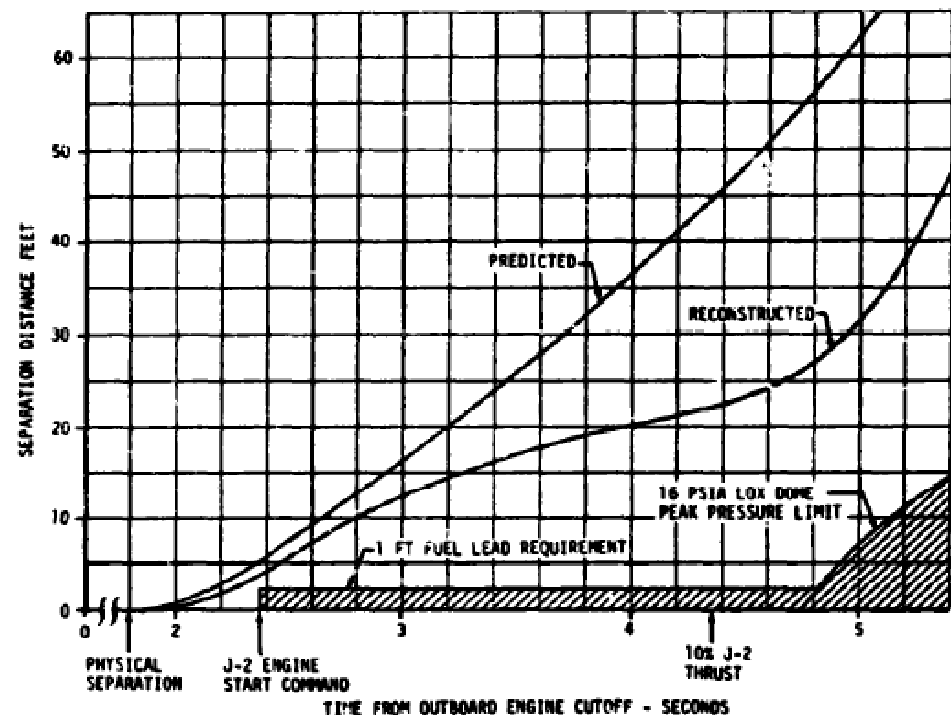


Figure 10-15. AS-510 Separation Distance



Anomaly Investigation Results

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- ◆ **The difference between the AS-510 observed and predicted separation distance is attributed to a greater F-1 engine "tail off" impulse than that used in the separation distance prediction.**
- ◆ **The F-1 thrust decay was normal and not appreciably different from previous (AS-505 through 509) flights.**
- ◆ **Analysis indicates that with an S-IC stage having only four retro motors, failure of one retro motor to ignite would result in marginal separation distances and, in the 3-sigma case, re-contact of the two stages.**
- ◆ **S-IC-11 and subsequent flight stages were equipped with eight retro motors rather than the planned four.**



One Retro Motor Failure Assessment Results

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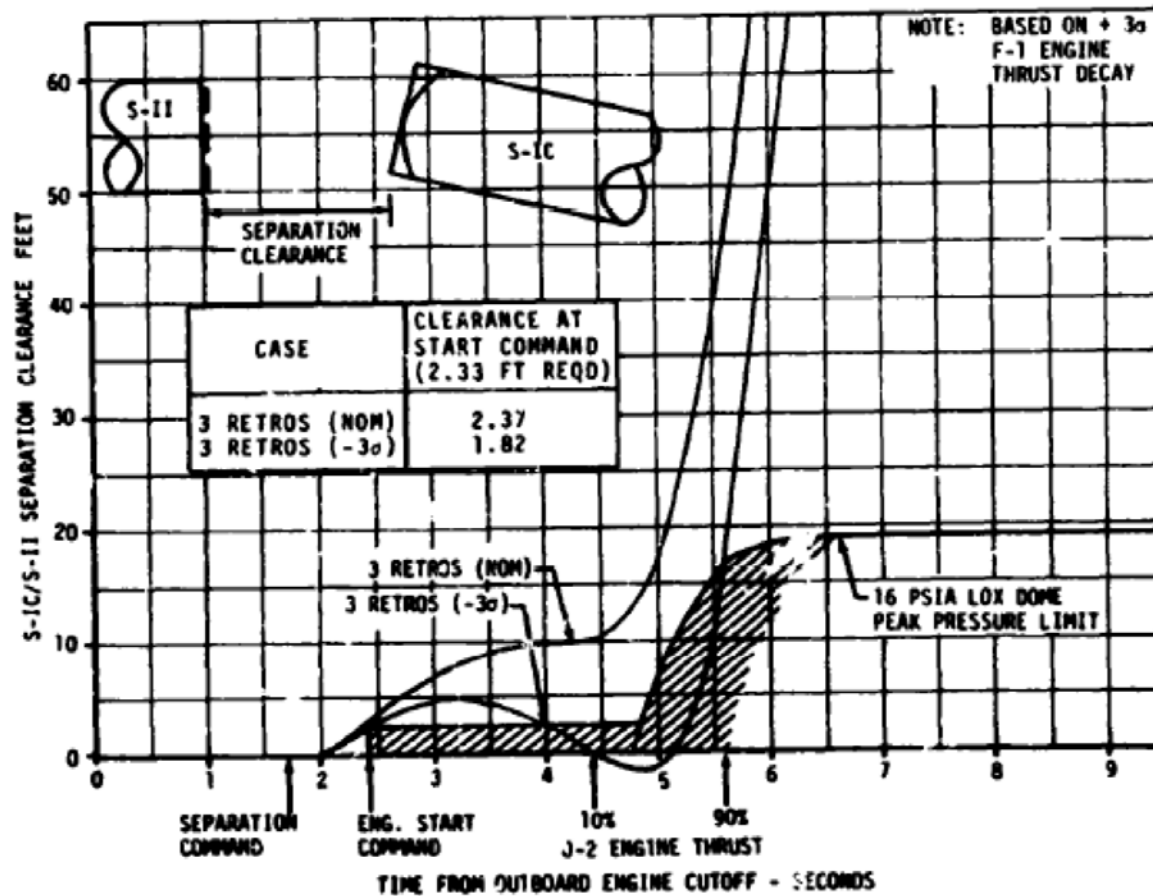


Figure 10-18. S-IC/S-II Separation Distance With Three Retro Motors



S-IC Stage Thrust Tail Off Based on Flight Experience (AS-505 Through 509)

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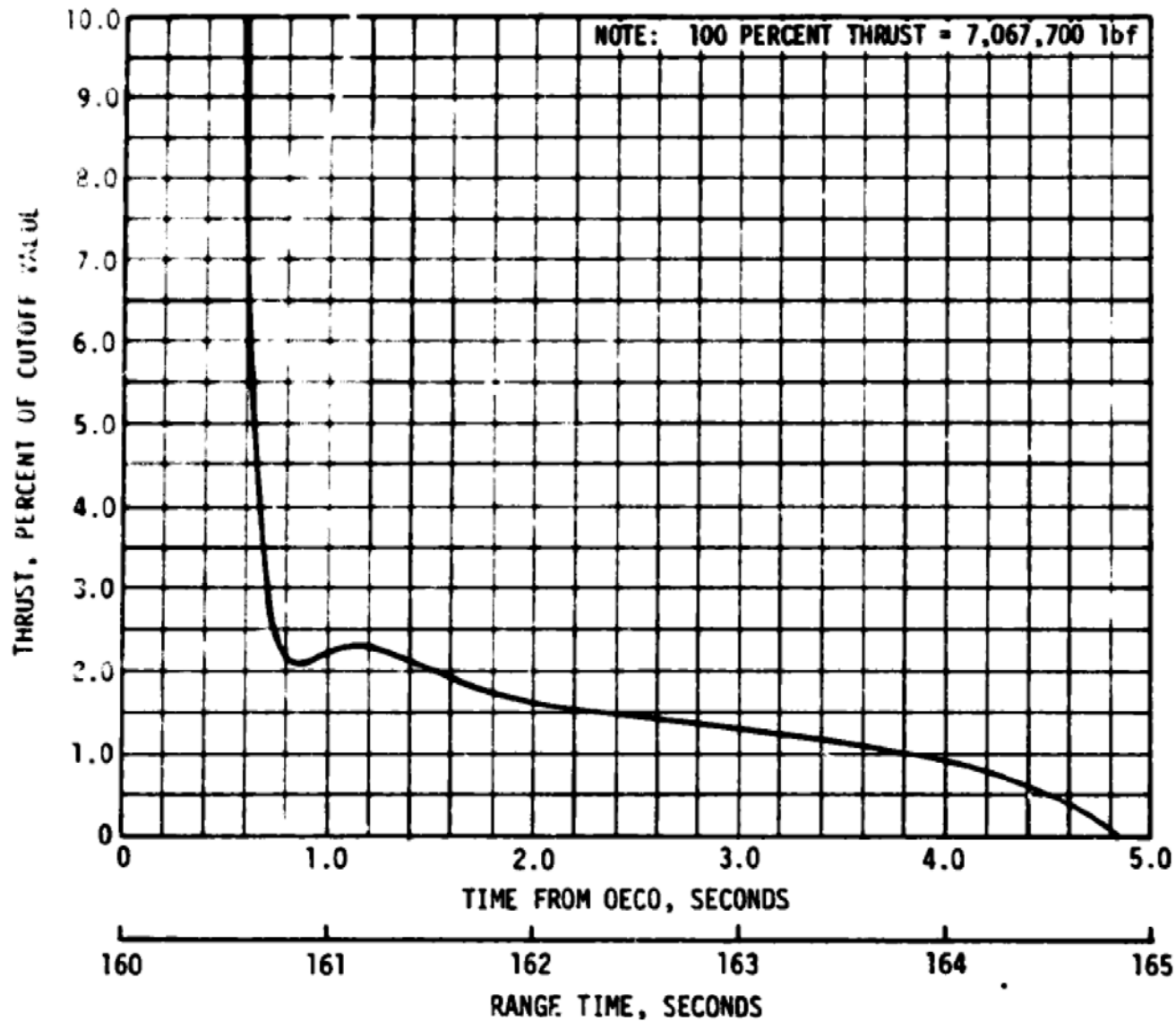


Figure 5-4. Normalized AS-510 Outboard Engine Thrust Decay



S-IC Stage Thrust Tail Off Compared with Change Analysis Assumption

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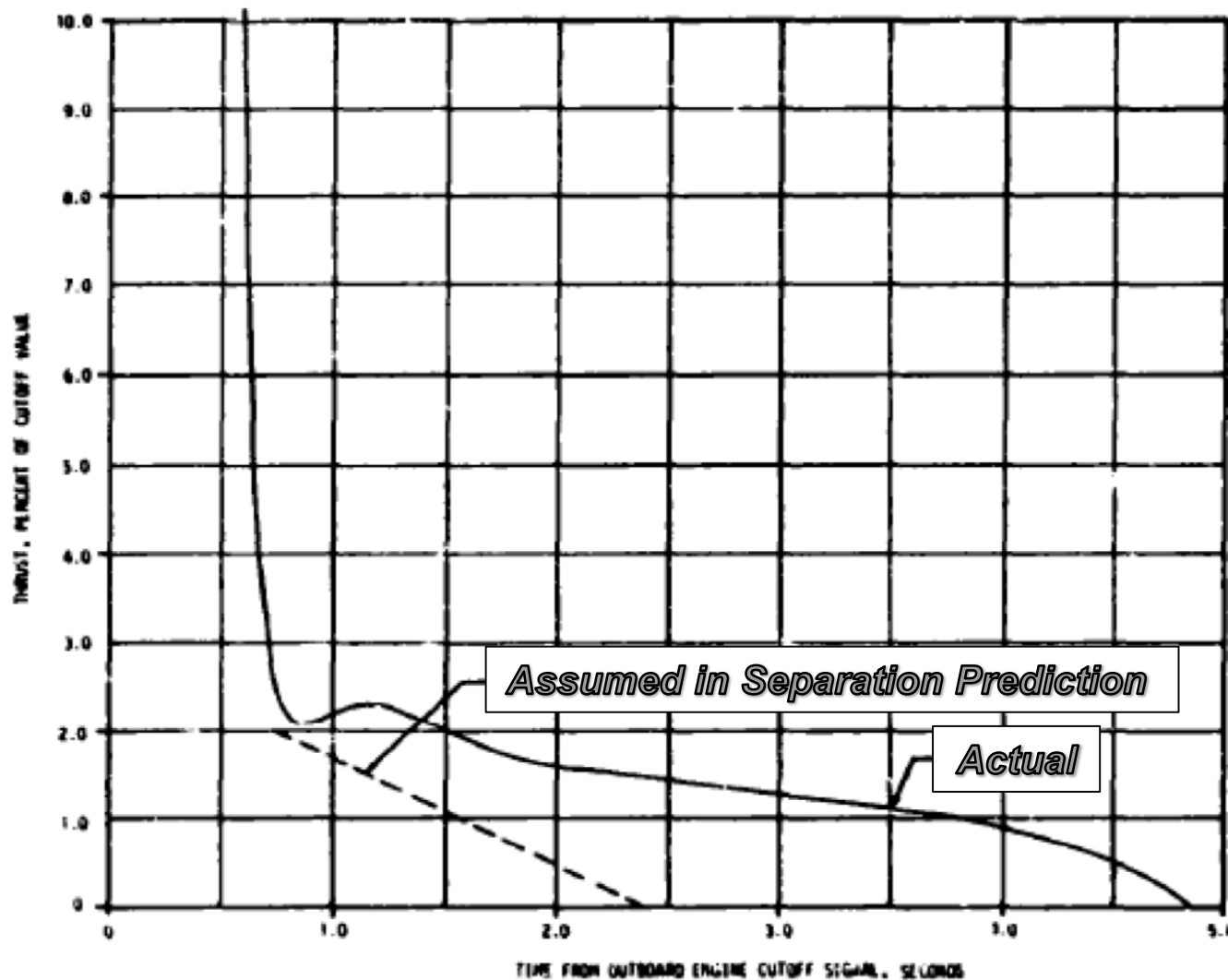
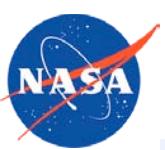


Figure 10-16. AS-510 Thrust Decay



Personal Observations from AS-510 Anomaly

(I was a Contractor Propulsion Group Employee at the Time)

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Underlying Causes

♦ Change Not Properly Coordinated Between Key Stakeholders

- Change Initially Reviewed by Technical Disciplines
- Propulsion Group Formal Recommendation for Reassessment of F-1 Tailoff and J-2 Buildup not Acted Upon.
 - Separation Dynamics Group Assumed Specification Minimum F-1 Tailoff - Assumption was Non-Conservative.
- Change Approved without Proper Interdisciplinary Review of Supporting Ground Rules, Assumptions, and Analyses Results.
- Checks and Balances not in Place - No “Signoff” Required by Technical Disciplines.

Fallout

- ♦ **After Formal Internal Investigation, Several Contractor Senior Managers were Removed from Assigned Responsibilities.**
- ♦ **NASA Senior Manager Career “Sidelined” – Never Recovered**

Lesson Learned: There Are NO Small changes!



Lessons Learned Illustration

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Propulsion Considerations for Stage Separation

◆ **Lesson: Thrust Tail Off Characteristics of the Lower Stage Propulsion are Critical in Stage Separation.**

- AS-510 Provides Evidence of Criticality
- Falcon F1 Flight 3 Provides Evidence of Criticality and Consequences.

◆ **Background**

- Designing vehicle systems for successful stage separation is dependent on understanding the interactions of:
 - **Lower Stage Propulsion System Thrust During Tail Off**
 - Upper Stage Start Transient Thrust
 - Force Characteristics of Separation Aids (e.g., retro motors, pneumatic pushers)
 - Aerodynamic Forces
 - Vehicle Dynamics
- Payload considerations provide motivation to separate a stage as soon as practical after its thrust is in tail off.
- Generally, “dragging along” a spent stage prior to separation costs payload.
- Note that a design that separates too early in tail off reduces payload due to additional separation aid capability required to compensate for residual tail off impulse.



Understanding Stage Thrust Tail Off

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◆ Determining Tail Off Characteristics Prior to First Flight is Challenging.

- Unless a Diffuser is Used in Ground Test, Liquid Engine and Solid Rocket Motor Nozzles Unchoke Before Reaching Low Thrust Levels Typically Required for Stage Separation.
- Thus, Defining the Thrust Profile Before First Flight is Challenging.

◆ Shuttle Experience

- Prior to STS-1, Only Ground Test Data Were Available for Low Level Solid Rocket Motor (SRM) Tail Off.
- SRM Ground Tests Conducted without a Diffuser.
- Ballistics Model Derived from Ground Test Data to Estimate Thrust Tail Off.
- Conservative Approach to Separation Taken – “Dragged” Boosters Longer than Indicated from Ballistic Model.
- Separation Timing Updated Using Approximately 9 Flights (17 Motors) and Conservatism Reduced.
- Additional Updates Performed as Requirements Were Modified and Methodology and Database Matured.



Understanding Lower Stage Thrust Tail Off

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♦ Falcon F1 Flight 3 Failure Discussion (Elon Musk):

- “The problem arose due to the longer thrust decay transient of our new Merlin 1C regeneratively cooled engine, as compared to the prior flight that used our old Merlin 1A ablatively cooled engine.”
- “As it turned out, a very small increase in the time between commanding main engine shutdown and stage separation would have been enough to save the mission.”
- “Unfortunately, the engine chamber pressure is so low for this transient thrust -- only about 10 psi -- that it barely registered on our ground test stand in Texas where ambient pressure is 14.5 psi.”
- “However, in vacuum that 10 psi chamber pressure produced enough thrust to cause the first stage to recontact the second stage.”

♦ Ares I-X Successful Separation

- Ares I-X First Stage Used a Space Shuttle Redesigned Solid Rocket Motor (RSRM) Flight Motor.
- Ares I-X Flight Design Made Use of Shuttle RSRM Flight Experience.
- Shuttle Models Derived from Flight Experience Used in Separation Sequence Definition.

Lesson Learned: Sacrifice Payload and Utilize a Conservative Sequence Until Thrust Tail Off Is Defined from Flight Experience.

Understanding Lower Stage Thrust Tail Off

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- ◆ Most Stage Tail Off Thrust Profiles are Repeatable Flight-to-Flight within Definable Limits.
- ◆ Once Flight Data are Available, the Nominal and Dispersed Tail Off Thrust Profile can be Defined and Refined.

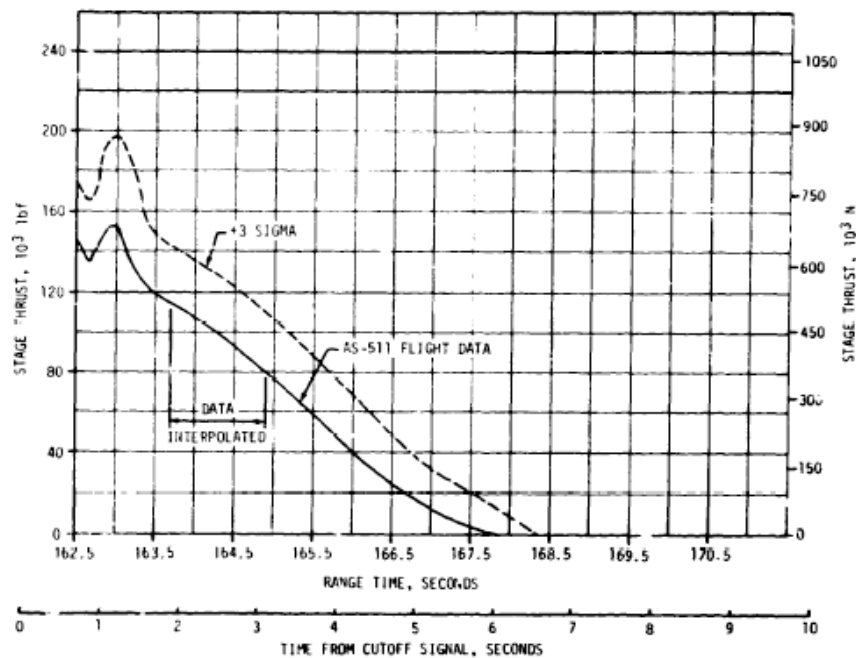


Figure 5-5. S-IC Thrust Decay

Lesson Learned: Build and Maintain a Flight Database for Stage Tail Off